Antenna Characterization for Wireless Power-Transmission System Using Near-Field Coupling

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Abstract

A fundamental study was focused on the investigation of wireless power transmission by near-field coupling from the view point of the antennas. Two types of antennas – dipole and loop antennas – were used as the transmitting antenna and the receiving antenna for electrical near-field coupling and for magnetic near-field coupling, respectively. The relationships among the power-transmission efficiency and the antennas' geometries, the antennas' electrical sizes, the impedance matching of the antennas, and the ohmic losses in the antennas and the impedance-matching circuits were clarified. Several observations were obtained, demonstrating the influence on the power-transmission efficiency of the impedance matching and ohmic losses in the wireless power-transmission system associated with near-field coupling.

Keywords: Electromagnetic induction; power transmission; electromagnetic coupling; antennas; impedance matching; wireless power transmission; wireless power transfer

1. Introduction

Studies on wireless power transmission (WPT) started as early as 100 years ago. Reinhold Rudenberg described the fundamental theory of electric power absorption by antennas early in 1908 [1]. Nikola Tesla developed the first practical wireless power-transmission system in 1904 [2], and revealed the system configuration in his US patent in 1914 [3]. Since then, there have been numerous research efforts involving both fundamental and applied studies on wireless power transmission. This technology has been widely applied, from the wireless charging of electronic devices to huge projects, such as the solar-power satellite (SPS) system [4]. However, this technology still has some problems. One of the most pressing challenges is how to maintain higher power-transmission efficiency (PTE) over longer transmission distances.

Recently, it was experimentally demonstrated that very efficient power transmission can be achieved by using the so-called evanescent resonant-coupling method, showing its potential for practical application [5]. It was shown that the evanescent resonant-coupling method can transmit energy for a longer distance than the previously used near-field induction method [6, 7]. The evanescent resonant-coupling method was shown to be more efficient than the far-field radiation method, wherein the vast majority of the energy was wasted, due to the transmission loss [8-10].

There have been many research studies following [5]. In [11], the power-transmission efficiencies of two dielectric disks and two capacitively loaded conducting-wire loops were calculated from the resonance width and the coupling coefficient based on the coupled-mode theory. This showed the applicability of a wireless power-transmission system in the presence of extraneous environmental objects. Wireless power transmission via magnetic resonant coupling was experimentally demonstrated in a system with a large source coil and either one or two small receivers. Resonance between the source and

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load coils was achieved with lumped capacitors terminating the coils [12]. It was also demonstrated that a wireless power-transmission system could be designed by conventional circuit theory and multistage filter theory in [13, 14]. We presented a practical wireless power-transmission system consisting of a large wire loop and a small wire loop with a parasitic square helical coil for an indoor application. We investigated the variation of the power-transmission efficiency when the location of the small loops was changed, and the resonance condition was destroyed by nearby scattering objects [15].

This research was focused on a wireless power-transmission system using near-field coupling to unify the concept of the evanescent resonant-coupling method and the conventional near-field induction method. The study was performed from the viewpoint of antenna theory instead of circuit theory. This was done by investigating antenna parameters such as the geometry of the transmitting and receiving antennas, the electrical size of the antennas, impedance matching for the antennas, the distance between the transmitting and receiving antennas, the conductor loss (ohmic loss) of the antennas, the ohmic loss of the matching circuits, and so on, in order to clarify the relationships among the power-transmission efficiency and these parameters. Two types of antennas, dipole antennas and loop antennas, were used as conical models to obtain some general conclusions. The power-transmission efficiency was strictly defined as the ratio of the received power at the receiving antenna and the input power at the transmitting antenna. The input impedance of the antennas, including the effects of near-field coupling between the transmitting and receiving antennas, was completely considered in evaluating the power-transmission efficiency. The study was performed using a full-wave EM analysis based on the Method of Moments (MoM).

2. Analysis Model and Method

In order to obtain a clear physical explanation of the relationship between the power-transmission efficiency and the antenna parameters, two simple antennas were used as the transmitting and receiving antennas. These were a straight wire dipole with a length l, shown in Figure 1, and a circular wire loop with a diameter of D, shown in Figure 2, operating as the antennas for electric coupling and magnetic coupling, respectively. The transmitting and receiving antennas were the same, and were separated by a distance d. The transmitting antenna was connected to a source with an internal impedance of Z_s, while the receiving antenna was loaded with an impedance Z_l.

These two wireless power-transmission systems can be expressed in the form of a two-port equivalent circuit, shown in Figure 3. The power-transmission efficiency can be evaluated by using the S parameters of the circuit as

$$\eta = \frac{P_l}{P_{in}} = \frac{|S_{21}|^2 \left(1-|\Gamma_l|^2\right)}{|1-S_{22}\Gamma_l|^2 \left(1-|\Gamma_{in}|^2\right)}, \tag{1}$$

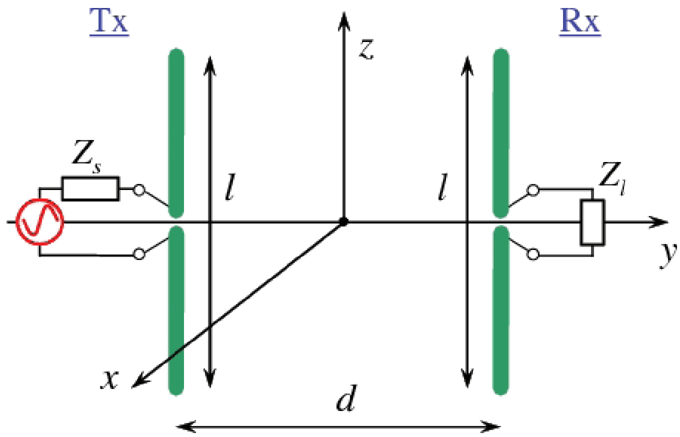

Figure 1. A wireless power-transmission system using dipole antennas.

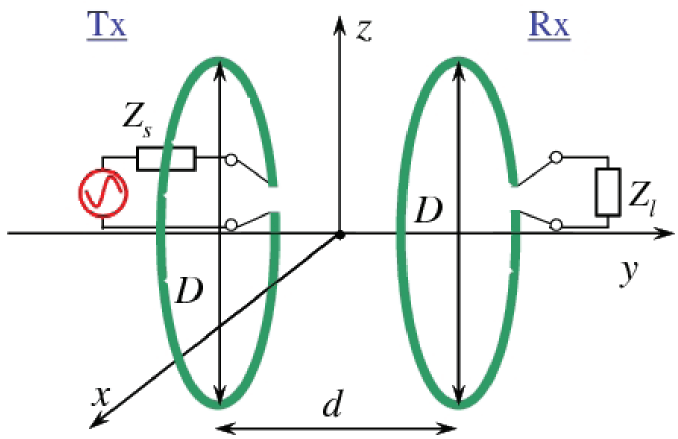

Figure 2. A wireless power-transmission system using loop antennas.

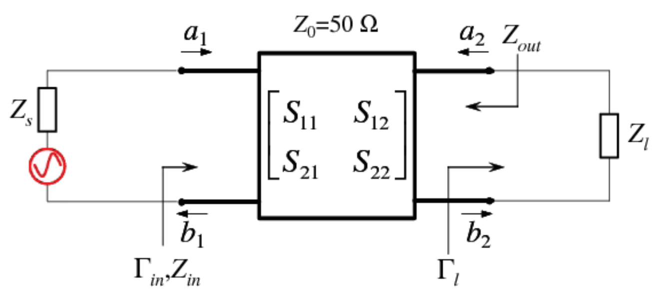

Figure 3. The two-port equivalent circuit for the analysis of a wireless power-transmission system.

where Γ_l is the reflection coefficient at the load Z_l, and Γ_{in} is the reflection coefficient at Port 1, expressed as

$$\Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{2}$$

and

$$\Gamma_{in} = S_{11} + \frac{S_{12} S_{21} \Gamma_l}{1 - S_{22} \Gamma_l}, \tag{3}$$

respectively. Here, S_{11}, S_{21}, S_{12}, and S_{22} were calculated by using the MoM, and a characteristic impedance $Z_0 = 50\ \Omega$ was assumed in the calculation.

3. Power-Transmission Efficiency for the Case of Conjugate Impedance Matching

In this section, the ohmic loss of antennas was ignored, to simplify the investigation. As a result, there were two kinds of power losses left in the wireless power-transmission system: the reflection loss, and the radiation loss. When the antennas' geometries and the distance between antennas are given, the radiation loss is determined. In this case, if both the transmitting and receiving antennas were perfectly impedance-matched with the feeding circuit and load impedance, respectively, the power-transmission efficiency reached the maximum value. The perfect impedance match was realized when the condition of complex-conjugate matching was satisfied at both Port 1 and Port 2. Because the transmitting antenna and receiving antenna are the same, the condition of conjugate impedance matching at two ports is equivalent to the relation

$$Z_{in} = Z_l^*, \tag{4}$$

where Z_{in} is the input impedance at Port 1, influenced by the reception port through near-field coupling, and Z_l^* is the complex conjugate of the load impedance, Z_l, at the reception port. Because Z_{in} depends on Z_l, Z_l should be tuned to a value Z_l^o to satisfy the relation of Equation (4). Z_l^o is called the optimal load impedance, and is dependent on the antenna geometry and distance between the transmitting and receiving antennas.

For the dipole system in Figure 1, the power-transmission efficiencies for different antenna lengths and distances between antennas are shown in Figure 4, when the receiving antenna was loaded with optimal load impedance, Z_l^o. It was found that the power-transmission efficiency could approach 100% if the antenna was small enough and the distance between antennas was short enough. A smaller dipole resulted in a higher efficiency when the dipole was electrically small. This result is theoretically true when the losses in antennas and matching circuits are ignored, because the radiation power decreases

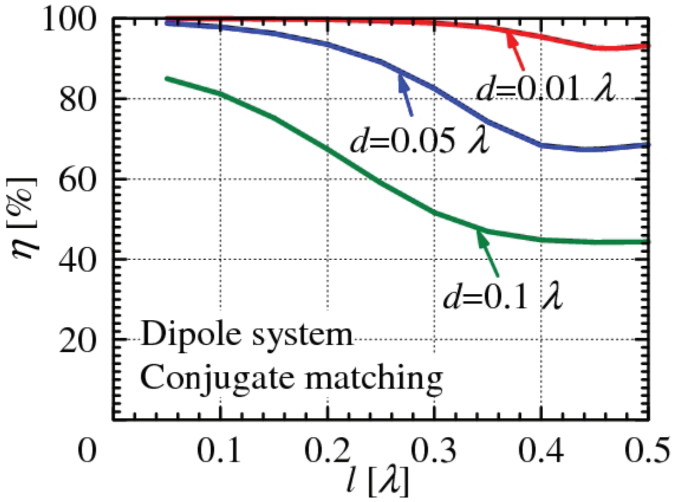

Figure 4. The power-transmission efficiency as a function of the dipole length for different distances between the antennas under the condition of complex-conjugate matching.

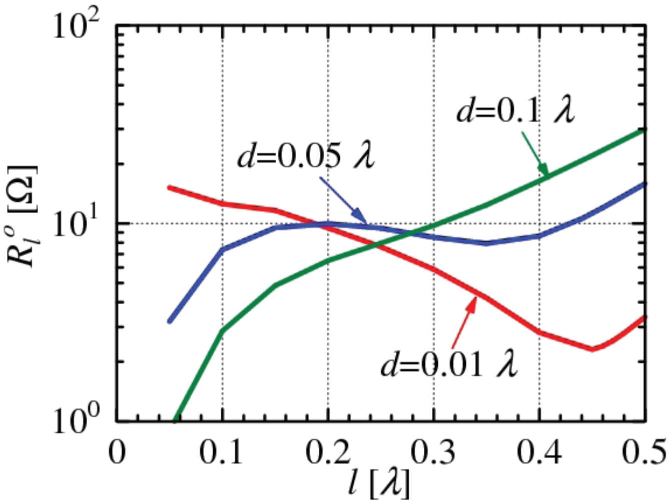

Figure 5. The resistance of the load impedance for the dipole system under the condition of complex-conjugate matching.

when the dipole length becomes short. The optimal load impedance, Z_l^o, is shown in Figure 5, for its real part, and Figure 6, for its imaginary part. It was shown that a short dipole required an extremely large value of reactance as the load impedance. In practice, this large reactance itself involves a large ohmic loss, which greatly reduces the power-transmission efficiency. The scenarios with consideration of losses in antennas and matching circuits will be discussed in the next sections.

For the loop system in Figure 2, the power-transmission efficiencies for different antenna diameters and distances between antennas are shown in Figure 7, when the receiving antenna was loaded with the optimal load impedance, Z_l^o. It was also found that the power-transmission efficiency could approach almost 100% if the loop was small enough and the distance between antennas was short enough. A smaller loop results in a higher efficiency when the loop is electrically small, approximately $D \le \lambda / 2\pi$. As was the same with the dipole case, a large value of the reactance component of Z_l^o was required to obtain a high efficiency near 100% by using electrically small loop antennas. Compared with the dipole system, the efficiency of both antennas had almost the same dependence on the antennas' sizes, except for a little decrease for the loop antenna, due to its anti-resonance.

It was known from the above results that near-field coupling for both the electrical-coupling approach and the magnetic-coupling approach could result in a power-transmission efficiency as high as almost 100%, if the antennas were electrically small enough and the distance between antennas was short enough. The concept of resonance was not necessary, but

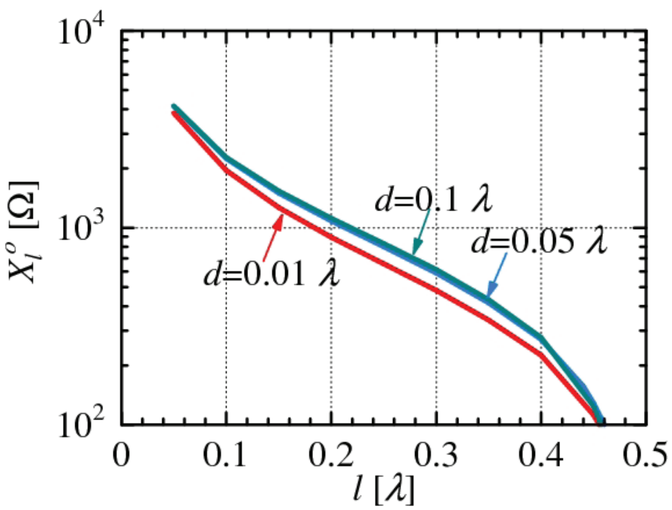

Figure 6. The reactance of the load impedance for the dipole system under the condition of complex-conjugate matching.

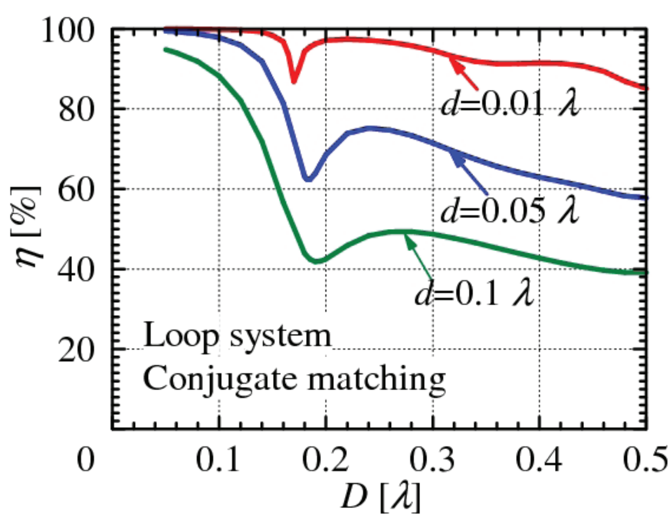

Figure 7. The power-transmission efficiency as a function of the loop diameter for different distances between the antennas under the condition of complex-conjugate matching.

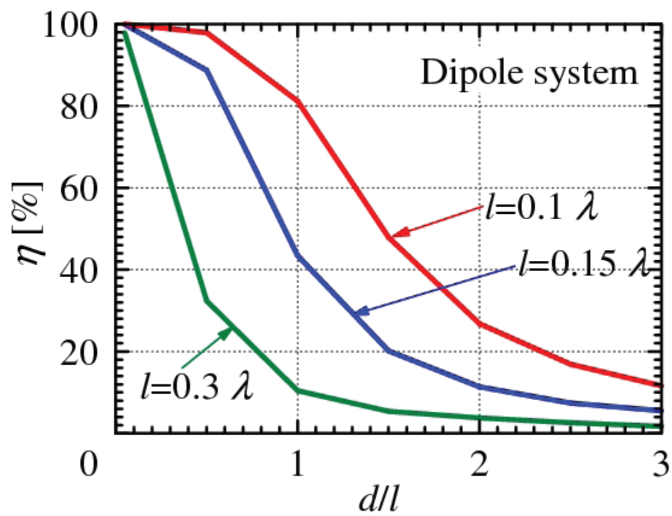

Figure 8. The power-transmission efficiency as a function of the distance between the antennas normalized by the antenna's size for the dipole antenna system.

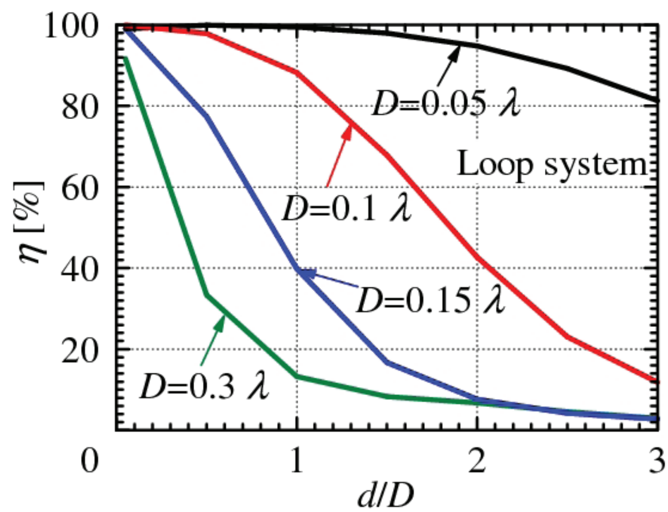

Figure 9. The power-transmission efficiency as a function of the distance between the antennas normalized by the antenna's size for the loop antenna system.

the conjugate-matching condition was essential for realizing a high power-transmission efficiency.

Generally speaking, a larger area of the near field, which contains the non-radiated inductive field, causes a longer distance for power transmission with a high efficiency. The area of the near field is determined by the antennas' geometries and the antennas' sizes. Therefore, we investigated the dependence of the power-transmission efficiency on the distance between antennas normalized by the physical size of the antennas for both dipoles and loops, to find which type of antenna was better in keeping a high power-transmission efficiency for a long transmission distance. The results are shown in Figure 8 for dipoles and Figure 9 for loops, where the distance between antennas, d, was normalized by the dipole's length, l, and by the loop's diameter, D, respectively.

It was found from these two figures that the efficiency of both antennas with the same values of l and D had almost the same dependence on the distance between antennas, if the distance, d, was normalized by the dipole's length, l, and the loop's diameter, D, respectively.

We can conclude in this session that if antennas are perfectly matched with the complex-conjugate impedance, the power-transmission efficiency can approach 100% when transmitting and receiving antennas are small enough and located within the near-field region of each other, and the concept of resonance is not required. A smaller size for the antennas results in a higher value of the power-transmission efficiency. Both the dipole and loop have almost the same power-transmission efficiency, if they have the same sizes. However, it is well known that the ohmic loss cannot be ignored, and even becomes a key factor in determining the antennas' performance, especially for those small antennas from the view of antenna engineering. Therefore, we should continue this study with consideration of the ohmic losses of antennas.

4. Power-Transmission Efficiency with Consideration of Ohmic Loss in Antennas

In this section, it was assumed that the antennas were made of a good conductor, and the condition of complex-conjugate matching was satisfied, to find the influence on the power-transmission efficiency due to the ohmic loss of the conductors. Two kinds of conductivity were assumed in the numerical analysis. One was 5.8×10^7 S/m, equivalent to that of pure copper. The other was 5.8×10^6 S/m, a more practical value for a good conductor. The frequency was 13.56 MHz for calculating the surface impedance of the antennas in the numerical simulation.

The efficiency variations with the antennas' sizes at a distance between antennas $d = 0.05\lambda$ for the dipole system and the loop system are shown in Figure 10 and Figure 11, respectively. Compared with the case of a perfect electrical conductor (PEC) plotted in these figures, the power-transmission efficiency was degraded due to the ohmic losses. The degradation due to the ohmic losses was dependent on the types and sizes of the antennas. An electrically small loop antenna was more sensitive to the ohmic loss than an electrical dipole, because the electrically small loop had a smaller input reactance, and thus a larger current, than the dipole antenna. When the distance between antennas was as large as $d = 0.1\lambda$, shown in Figure 12, the degradation of the loop system became much more serious.

From the above study, it was found that the reactance part of the optimal load impedance was very large, showing a large inductance value for electrically small dipole antennas, and a small capacitance value for electrically small loop antennas, to satisfy the condition of complex-conjugate matching. The optimal load impedance should have a very low Q value, because the resistance component is, relatively, very small. However, it is very difficult in practice to realize this large load impedance with a very low Q value. In the next section, the matching circuits were added to the wireless power-transmission system, and the ohmic loss in the matching circuits was further considered in the numerical analysis.

5. Power-Transmission Efficiency with Consideration of Ohmic Losses in Matching Circuit

The matching circuit is usually used for $50\ \Omega$ matching, but it was introduced here for canceling the large value of the

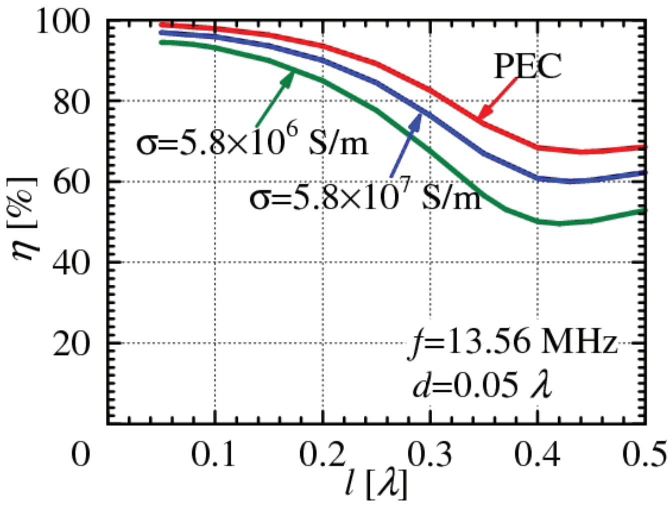

Figure 10. The power-transmission efficiency as a function of the dipole length for different conductivities of antennas, when the distance between the antennas was $d = 0.05\lambda$ and the condition of complex-conjugate matching was satisfied.

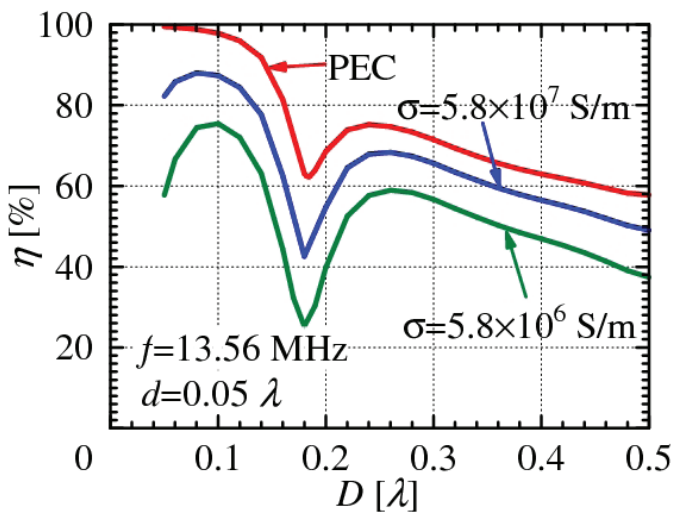

Figure 11. The power-transmission efficiency as a function of the loop diameter for different conductivities of antennas when the distance between antennas was $d = 0.05\lambda$ and the condition of complex-conjugate matching was satisfied.

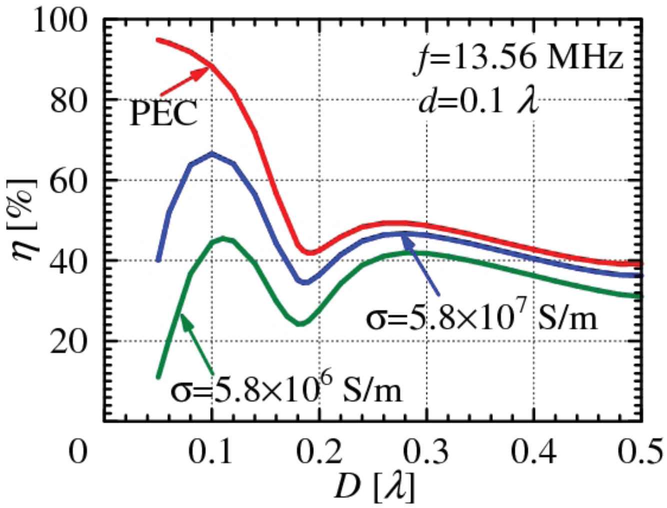

Figure 12. The power-transmission efficiency as a function of the loop diameter for different conductivities of antennas when the distance between antennas was $d = 0.1\lambda$ and the condition of complex-conjugate matching was satisfied.

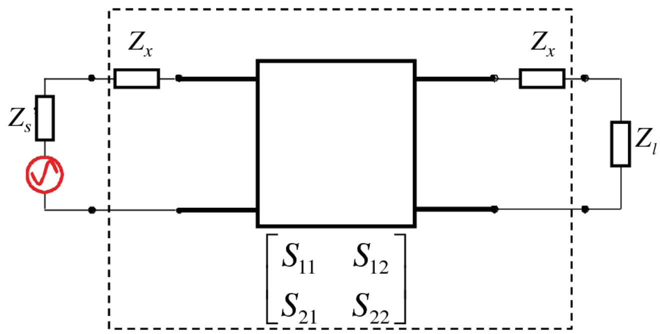

Figure 13. The two-port equivalent circuit, including the matching circuit.

reactance component of the optimal load impedance. Because the frequency bandwidth was not considered, the matching circuit could be very simple: it was just composed of one lumped element with an impedance Z_x, connected with the load and source in series, as shown in Figure 13. Introduction of the single-element matching circuit is equivalent to the concept of designing small antennas, if the bandwidth is not the most important fact to be considered. The impedance, Z_x, had the same reactance component of Z_l^o, while its resistance was determined by the Q value of the lumped element, reflecting the ohmic loss of Z_x, defined as

$$Z_x = \frac{\left|X_l^o\right|}{\mathrm{Q}} + jX_l^o, \tag{5}$$

where X_l^o is the imaginary part of the optimal load impedance Z_l^o, and Q is the Q factor of the matching impedance, Z_x.

Because of the existence of the matching circuit, the optimal load impedance to obtain the maximum power-transmission efficiency was changed, and had to be calculated with consideration of the matching circuit. If the equivalent circuit included the matching circuit as shown in Figure 13, the optimal load impedance, Z_l^o, for complex-conjugate matching could be obtained according to the approach described above. This was true if the S parameter was evaluated from the circuit block including the transmitting and receiving antennas, and the matching circuits at both ports, which is enclosed by a dashed line in Figure 13.

The power-transmission efficiencies for the dipole system and for the loop system with different Q values in the matching circuit are shown in Figure 14 and Figure 15, respectively.

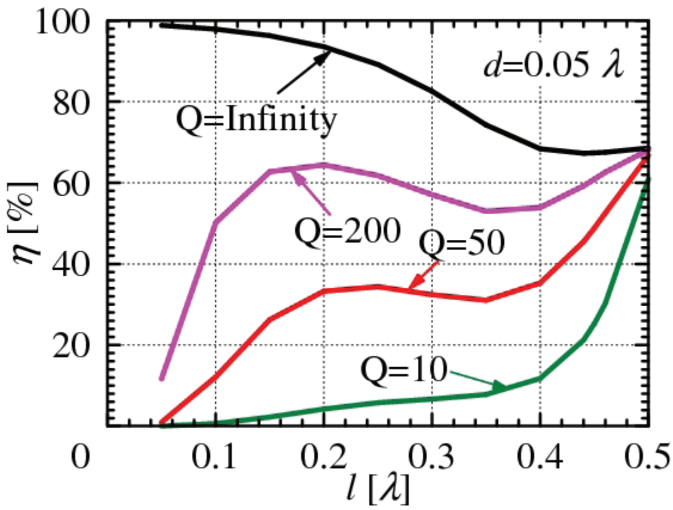

Figure 14. The power-transmission efficiency as a function of the dipole length for different Q values in the matching circuit when the distance between the antennas was $d = 0.05\lambda$ and the condition of complex-conjugate matching was satisfied.

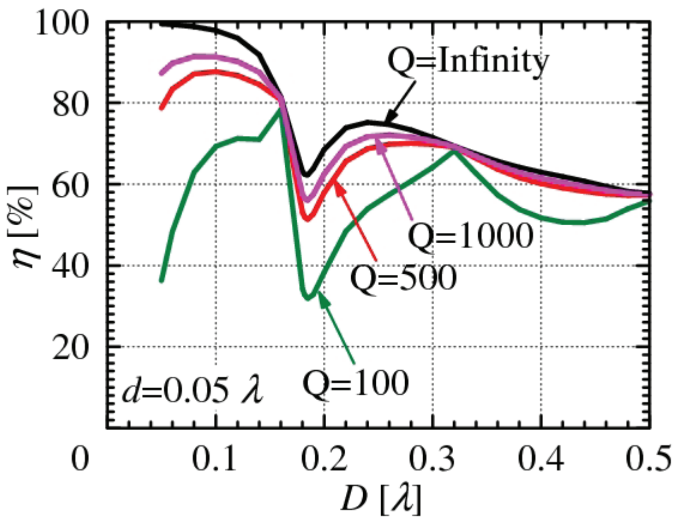

Figure 15. The power-transmission efficiency as a function of the loop diameter for different Q values in the matching circuit when the distance between the antennas was $d = 0.05\lambda$ and the condition of complex-conjugate matching was satisfied.

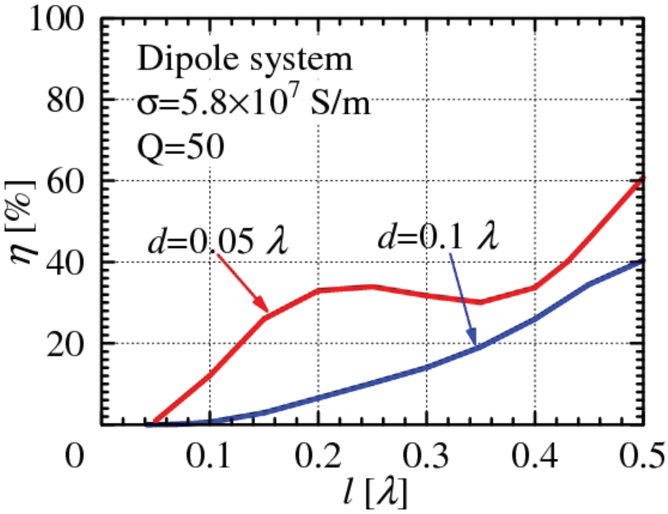

Figure 16. The power-transmission efficiency as a function of the dipole length for different distances between the antennas when the ohmic losses were considered in both the antennas and matching circuits, and the condition of complex-conjugate matching was satisfied.

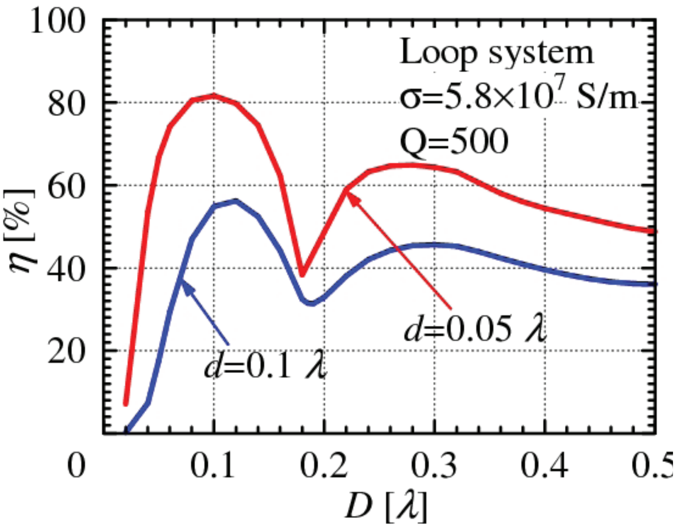

Figure 17. The power-transmission efficiency as a function of the loop diameter for different distances between the antennas when ohmic losses were considered in both the antennas and matching circuits, and the condition of complex-conjugate matching was satisfied.

Here, the ohmic loss in the antennas was not considered in the simulation model. It was noted that the lumped element was an inductor for the dipole system, while it became a capacitor for the loop system. The performance chart from those commercial products of inductors and capacitors for RF applications showed that the Q value of a capacitor was much higher than that of an inductor. Because of this fact, the range of Q values for the dipole and loop systems was different in the numerical experiment.

It was found that a small antenna was good at increasing the power-transmission efficiency as high as 100% in the case of $Q = \infty$. However, if the ohmic losses were considered, the situation became quite different. The efficiency was degraded very much when the antenna became small. It was also found that the efficiency of the loop system was generally much higher than that of the dipole system, if the Q value difference between the dipole and loop was considered. Even if the Q value had the same value, the efficiency of the loop system was also higher than that of the dipole system, especially when the antenna was electrically small.

Finally, the ohmic losses in both antennas and matching circuits were considered in comparing the dipole and loop systems. The efficiencies with the distance between antennas as a parameter for the dipole system and loop system are shown in Figure 16 and Figure 17, respectively. The Q value in the matching circuit was 50 for the dipole system, and was 500 for the loop system. The efficiency for dipole system rapidly became small when the antenna became small. However, for the loop system, there was an optimal loop size, around $D = 0.1\lambda$ when $d = 0.05\lambda$, and around $D = 0.12\lambda$ when $d = 0.1\lambda$. This was because the efficiency was reduced due to the increase of the radiation loss when D was large, and was also reduced due to the increase of the ohmic losses when D was small. However, for the dipole system, the optimal antenna size was not clear, because the effect of ohmic losses in the matching circuit was a dominant factor in determining the power-transmission efficiency when antenna was electrically small.

6. Conclusions

In this research, a wireless power-transmission system was numerically analyzed by using canonical models, including a dipole system and a loop system, to investigate the relationships among the power-transmission efficiency and the antennas' geometries, sizes, distances between antennas, and ohmic losses in the antennas and matching circuits. We can summarize the results from the numerical experiments as follows:

- It was theoretically true that the maximum efficiency could be obtained by loading the antenna with the conjugate-matching impedance if the antennas' geometries and the distance between antennas were given, while the concept of resonance was not required.
- A high efficiency, near 100%, could be achieved in the near-field region when the antenna was small enough, under the assumption of the conjugate-matching condition and without ohmic losses.
- The efficiency was degraded when the ohmic losses of the antennas was considered. The loop system was more significantly affected by the ohmic losses than the dipole system.
- In practice, the loop system was superior to the dipole system in achieving high efficiency, if the ohmic losses

of both the antennas and the matching circuits were considered. The superiority of the loop system was very obvious if the Q factor of the lumped electrical elements in the matching circuits was defined in a practical range.

- An optimal size of loop existed for the maximum efficiency, the value of which was dependent on the distance between antennas.

Although conical models of the antennas were used in the numerical-analysis models, these results and observations are general and fundamental. They can provide theoretical insight into how to design systems for wireless power transmission using near-field coupling. In practice, the antenna geometry can be designed to be very complex. For example, a loop antenna together with a helical loop as a parasitic element was usually used in previous studies. However, the parasitic element in this case is theoretically equivalent to increasing the electrical size of the original loop antenna, and the results in this study are still applicable.

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Introducing the Feature Article Authors

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